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IMPACT IGNITION OF LIQUID PROPELLANTS

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The report describes a preliminary study of the impact ignition of liquid propellants. In one experimental set up, two dimensional cavities were shocked and the cavity collapse studied by both high-speed framing and streak photography. Cavities in water and liquid propellant (LGP 1846) were studied. Cavity sizes were in the range 1 - 7 mm and shock strengths in the range up to 1.5 GPa were used. The cavities were observed to involute and produce a high speed jet which crossed the cavity and impacted the downstream wall sending a shock into the surrounding material. The gas in the cavity was heated by rapid compression achieving temperatures sufficient to cause gas luminescence. Finally, the jet penetrated the downstream wall of the cavity to form a pair of vortices which travelled downstream with the flow. Jet velocities up to ca. 500 m s⁻¹ were observed. A more general discussion of cavity collapse and the initiation of explosion is presented in Appendix 1 (Bourne and Field 1991, Proc.Roy.Soc. 435, 423-435). In the second series of experiments, drop-weight impacts were performed on layers of propellant of various geometries using a transparent anvil apparatus. This experimental set-up allows high-speed photographic recording of the event. The drop weight had a mass of 5 kg and was dropped from a height of 1.3 m. No ignition events were observed. Flow velocities of up to about 200 m s⁻¹ were observed. Of particular interest was the production of filaments of cavities in the impacted layers.

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IMPACT IGNITION OF LIQUID PROPELLANTS

INTRODUCTION

This preliminary study was begun at the request of Dr. J Knapton and in response to the accidental initiation of the US liquid propellant LGP1846 (UK designation LP101) during its removal from a 105 mm regenerative liquid propellant gun. The unexpected ignition was suspected to have resulted from impact and/or cavitation. Maximum pressures were reported to be in excess of 600 MPa. Friction between moving parts and viscous heating of the propellant were eliminated as causes of the ignition. It was observed that other liquid propellants held at temperatures greater than 80°C were much more sensitive as a result of water loss.

The composition of the propellant was as follows:-

Hydroxylammonium nitrate (HAN)	63.23%
Triethanol ammonium nitrate (TEAN)	19.96%
Water	16.81%

The initiation of reaction in an explosive is a thermal process. Mechanical energy dissipated by the passage of a compression wave through an explosive can be degraded into heat in order to cause ignition. In general bulk heating of a material is insufficient to cause ignition but heating in small, localised regions, called hot spots, allows energy concentrations from which thermal explosion can proceed. Several mechanisms leading to hot-spot formation in the cavity collapse process have been identified:-

- (i) gas phase heating,
- (ii) hydrodynamic effects resulting from the compressibility of the material,
- (iii) viscous heating of the material.

To date two types of experiment have been attempted, the first involves cavity collapse (Section 2) and the second drop-weight impact (Section 3). The paper in the appendix reviews the literature on shock induced cavity collapse and gives framing and streak data on phenomena which occur when cavities are collapsed in liquids; both inert and reactive systems were examined.

2. BUBBLE COLLAPSE IN A LIQUID PROPELLANT

2.1 Experimental

Figure 1 shows the apparatus designed to test the propellant. The shock stimulus was provided by the hot wire ignition of 27 mg of granular lead azide in a plastic case. The fuse was fired by a 16 J pulse from a switched EHT source. This vaporised the bridge-wire. A Bowen professional flash unit discharging 250 J over ca. 2 ms lit the event from behind. A graduated diffuser was placed between the cavity and the rear confinement. The liquid was enclosed within PMMA blocks spaced by a mild steel insert. The fuse lay within the liquid.

The cavity was introduced by injecting a bubble of gas beneath a thin wire supporting a plastic shim and then bent into a semicircle. The bubble size and position could be altered by suitably bending and translating the wire. Cavity sizes in the range 1-7 mm both circular and elliptical were collapsed. The ideal gas laws along with the assumption that the gas entrapped within the cavity is collapsed adiabatically give the final temperature, T_f , through the equation

$$T_f = T_i \left(\frac{V_i}{V_f} \right)^{\gamma-1}, \quad [1]$$

where T_i is the initial temperature within the cavity, V_i and V_f are the initial and final volumes of the gas enclosed, and γ is the ratio of the principal specific heats for the gas. It can be seen that increasing the value of γ will increase the final temperature achieved within the cavity. To this end a monatomic gas was used whose atoms have fewer degrees of freedom. Argon was chosen for this purpose.

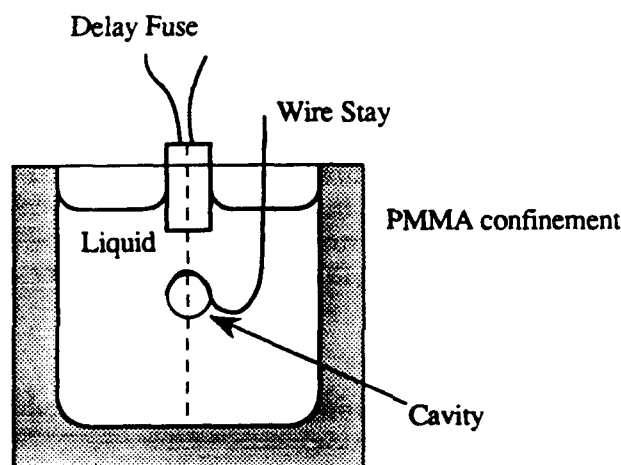


Figure 1. Experimental arrangement employed in the propellant tests. The cavity was backlit and photographed with high-speed streak and framing cameras.

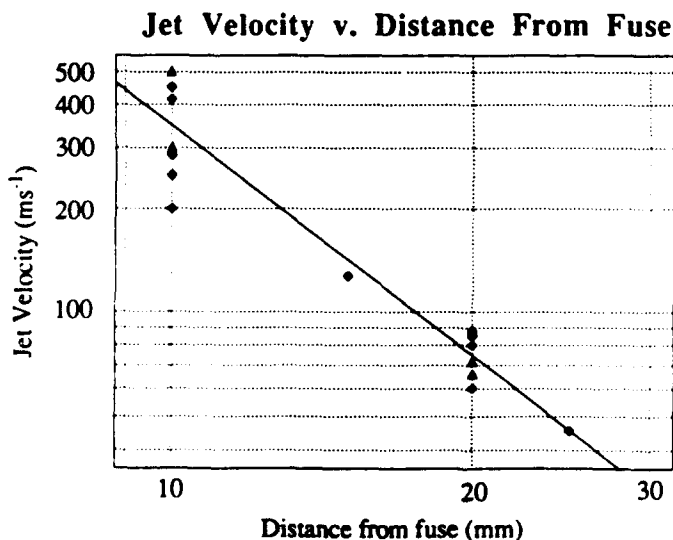
The cameras used were a Hadland Imacon 790 and 792. The former was streaking at a speed of $800\text{--}1100 \text{ ns mm}^{-1}$. The latter was framing at a rate varying from 2×10^5 – 5×10^5 frames per second (fps). The EHT pulse generator, flash and the camera were fired sequentially from a Hadland 103 delay generator.

The cavity was placed 25 mm, 20 mm, 15 mm and 10 mm from the base of the fuse. At each distance simultaneous streak and framing sequences were recorded. The cavity size and gas content were varied. A critical parameter reflecting the violence of the collapse is the collapse time of the cavity (defined for these asymmetric collapses to be the time from which the shock passes the upstream wall to the time at which the jet impacts the downstream wall). Jet velocity can be calculated from measured collapse time since the initial dimensions of the cavity are known.

The calculated jet velocities are plotted against the distance from the fuse in figure 2. The axes are logarithmic. The shock pressure may be expected to decay according to a reciprocal square law with distance so that the straight line behaviour is not surprising. There is a scatter of velocities at each distance. This can be explained in terms of the variable output of the delay fuse since it contains only a loose powder of primary explosive. Streak records of the shock velocity at the cavity wall confirm this variability. Accurate determination of shock pressure may be attempted if the Hugoniot relation for the propellant were known. Assuming that it would be close to that for water measured shock velocities suggest a pressure of ca. 1.5 GPa at the closest distance from the fuse (see figure 3).

2.2 Sequences

Three sequences are presented showing typical behaviour for collapse in water and propellant. Figure 4 shows an elliptical cavity collapsing in water, the cavity being placed 20 mm from the fuse. A millimetre grid is visible behind the cavity. A jet forms in frame 2 and crosses the cavity impacting the downstream wall in frame 8. The collapse is slow taking 80 μ s and the jet velocity is ca. 80 m s^{-1} . When equivalent cavities were collapsed in propellant no initiation was observed.



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Figure 2. Jet velocity plotted against distance from the fuse. The axes are logarithmic.

In figure 5 two sequences are shown where similar sized cavities are placed 10 mm from the fuse. The upper sequence shows collapse in water and the lower sequence shows a collapse in LGP1846. In both cases the collapse is rapid with jet velocities ca. 200 m s^{-1} . After the jet hits the downstream wall it penetrates it and forms a pair of linear vortices which move downstream in the flow after collapse. This region

appears dark in the sequences. If reaction were occurring one would expect much greater dark areas to be apparent due to reaction products at the jet impact site. In general this was not observed.

Figure 6 shows the single occasion on which reaction was initiated in the propellant. The reacting area can be seen as the dark region below the wire loop. Products from the detonator can be seen entering from above. It is believed that this initiation was due to an especially violent reaction in the delay fuse which contained only a loose powder of material. It is clear that the conditions of pressure in the shocked-fluid are close to the critical parameters for initiation in the propellant.

Figure 7 shows a streak record for the collapse of a bubble in water. A schematic of the collapse is shown below onto which figures representing wave and wall velocities in m s^{-1} have been appended. The incident shock enters from above at 2357 m s^{-1} and initiates collapse of the cavity. The jet crosses the cavity and impacts the downstream wall sending out a rebound shock into the surrounding material. The bubble remnants travel downstream with the flow whilst the detonator products enter the sequence as a dark area from above.

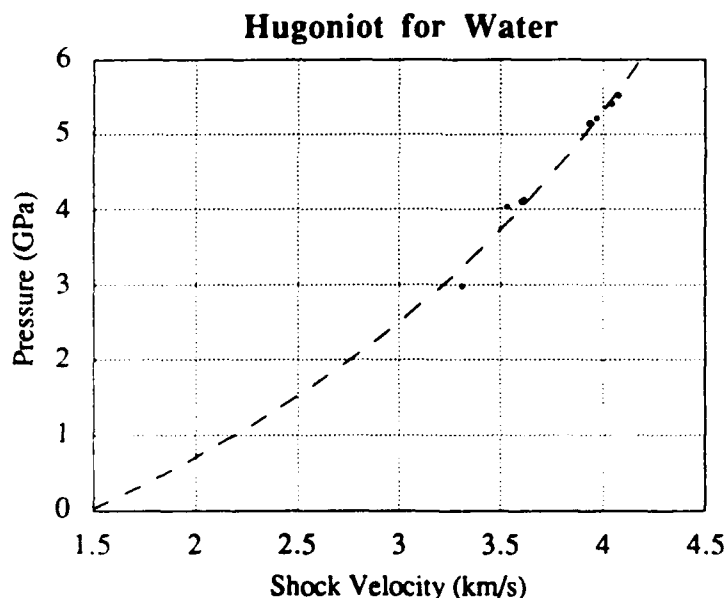


Figure 3. Hugoniot for water; fifth order polynomial fitted to data from Marsh; LASL Shock Hugoniot Data, University of California press, 1980. Low pressure data only shown.

Conclusions

The framing photography shows that the appearance of the cavities collapsed in water is almost identical to that observed for cavities collapsed in propellant at each distance. Streak photography also bears out these findings. It is thought that the collapses are insufficiently violent to result in reliable initiation of the propellant. In one sequence only there appears to have been a reaction in the propellant. It is possible that the output from the fuse was anomalously high in this case.

Elliptical cavities with major axis aligned at an angle to the shock front were collapsed. It was expected that the jet should travel in a direction perpendicular to the shock front. This was not found. The jet was found to travel down the major axis of the cavity.

3. HIGH-SPEED PHOTOGRAPHY: DROP-WEIGHT APPARATUS

The drop-weight apparatus shown in figure 8 was originally developed by Blackwood & Bowden (1952) and has more recently been extensively employed in the study of the sensitivity to impact of a wide range of energetic materials (see the references by Heavens & Field (1974), Swallowe & Field (1981), Field, Swallowe & Heavens (1982), Krishna Mohan & Field (1984), Krishna Mohan *et al.* (1984), and Field *et al.* (1985)). The material to be tested (in this case a liquid gun propellant) is compressed between toughened glass anvils at an impact velocity of typically 4.5 m s^{-1} . The drop weight (mass 5 kg) which bears the upper anvil is dropped from a height of up to 1.3 m and is guided by three rods to ensure a planar impact. Shortly before contact, the mirror within the weight comes into alignment to complete the optical path from a xenon flash light source, through to the high-speed camera. A simple electrical contact is made at this point and triggers the light which has flash duration of 1 ms. The camera, an AWRE C4 rotating mirror camera, is of the continuous access variety so that synchronization is not required. The full length of film (140 frames) is scanned in approximately 1 ms so that the duration of the flash carries out the function of a shutter. There is often over-writing, or double exposure, of some frames (unless the anvils shatter) but it is not usually troublesome; indeed it can be valuable in comparing initial and final states.

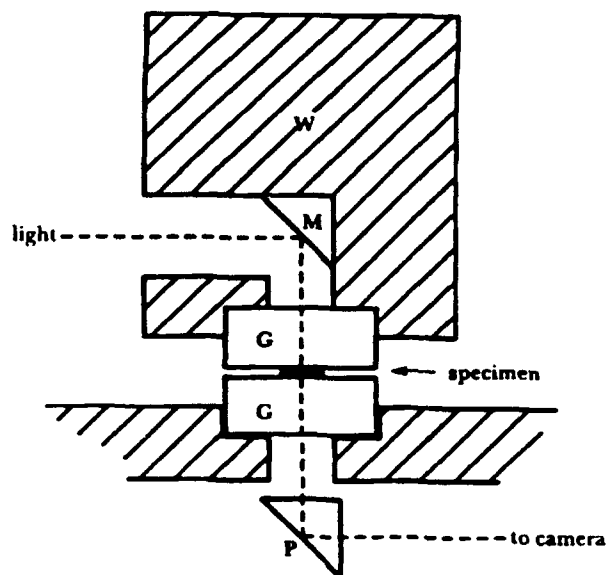


Fig. 8 Schematic diagram of the dropweight apparatus modified for high-speed photography. W, weight; M, mirror; G, glass anvils; P, prism.

The view seen by the camera is along the axis of compression so that what is observed is the expansion of the outline of the drop(s) seen in silhouette against the transmitted background light. Figures 9 and 10 show this behaviour for single drops deformed in this apparatus at room temperature. The circle of contact with the upper anvil can be seen expanding in the first few frames. Fine-scale streaming of liquid out from the circumference occurs when this contact circle reaches the periphery of the drop. A corresponding internal filamentous structure can also be seen probably due to cavitation. When the glass anvils finally come into intimate contact, the expansion of the drops accelerates rapidly.

A common cause of ignition of solid and liquid explosives in this geometry is the compression of a gas space (Bowden & Gurton 1949). So in this work, experiments were performed on annuli of liquid stabilised by petroleum jelly (figures 11 and 12). This allows a control gas pocket to be trapped and compressed. An alternative mechanism for trapping gas in energetic liquids occurs when two separate drops are deformed close to each other so that they expand into each other (Field *et al.* 1982). The best effect was obtained with two drops of dissimilar size. Figure 13 shows just such a sequence for LGP 1846. Notice the lateral jets formed by the collision of the expanding drops. None of the sequences reported here showed initiation.

REFERENCES

- Blackwood J.D. & Bowden F.P. 1952 "The initiation, burning and thermal decomposition of gunpowder" *Proc. Roy. Soc. Lond. A* 213 285
 Bowden F.P. & Gurton O.A. 1949 "Birth and growth of explosion in liquids and solids initiated by impact and friction" *Proc. Roy. Soc. Lond. A* 198 350

- Field J.E., Palmer S.J.P., Pope P.H., Sundararajan R. & Swallowe G.M. 1985 "Mechanical properties of PBX's and their behaviour during drop-weight impact" in *Proc. 8th Int. Symp. on Detonation*, Albuquerque, U.S.A.
- Field J.E., Swallowe G.M. & Heavens S.N. 1982 "Ignition mechanisms of explosives during mechanical deformation" *Proc. Roy. Soc. Lond. A* **382** 231
- Heavens S.N. & Field J.E. 1974 "The ignition of a thin layer of explosive by impact" *Proc. Roy. Soc. Lond. A* **338** 77
- Krishna Mohan V. & Field J.E. 1984 "Impact initiation of hexanitrostilbene" *Combustion and Flame* **56** 269
- Krishna Mohan V, Field J.E. & Swallowe G.M. 1984 "Effects of physical inhomogeneities on the impact sensitivity of solid explosives: A high-speed photographic study" *Combustion Sci. and Tech.* **44** 269
- Swallowe G.M. & Field J.E. 1982 "The ignition of a thin layer of explosive by impact: The effect of polymer particles" *Proc. Roy. Soc. Lond. A* **379** 389

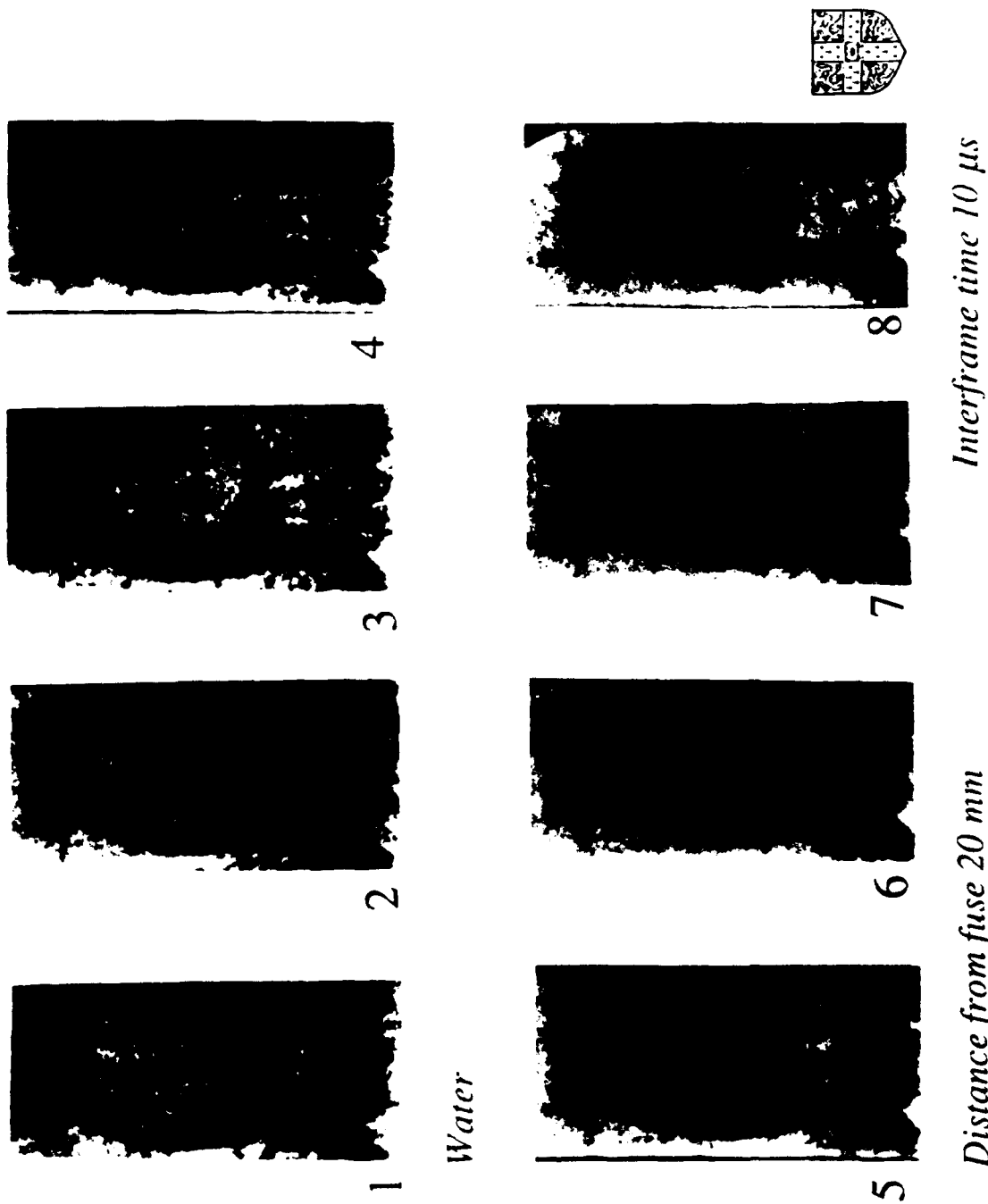
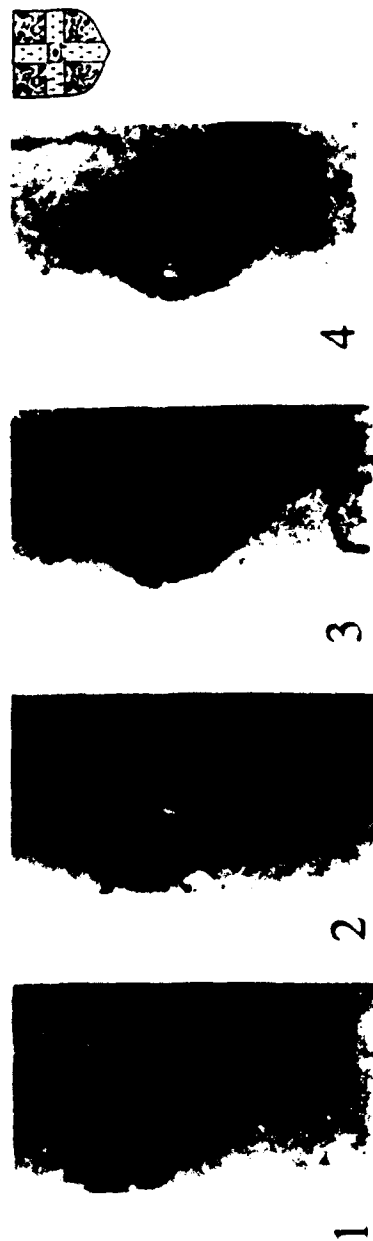
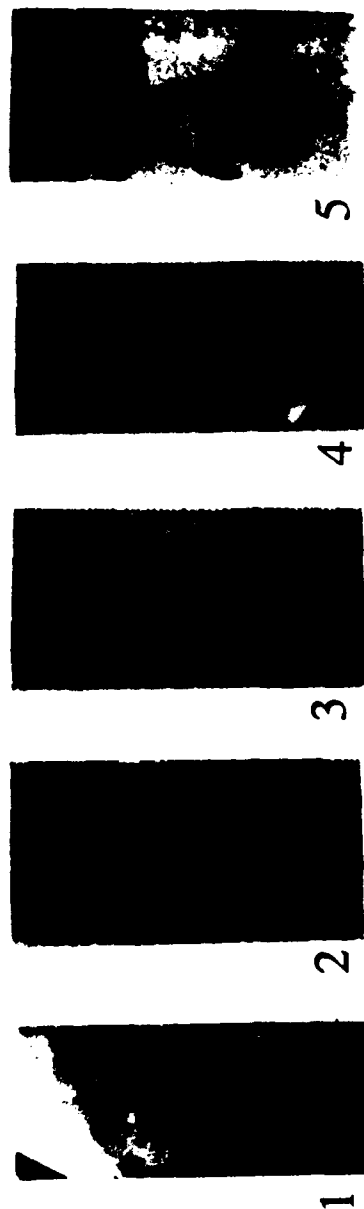


Figure 4. Elliptical cavity collapses in water. It is 20 mm from the fuse. A jet crosses the cavity and impacts on the downstream wall in frame 8.



Water

Interframe time $8 \mu s$



Propellant

Distance from fuse 10 mm

Figure 5. Cavities collapse in (top) water and (bottom) propellant. They are placed 10 mm from the fuse. The collapse is much more rapid than in figure 4 but no initiation is observed.

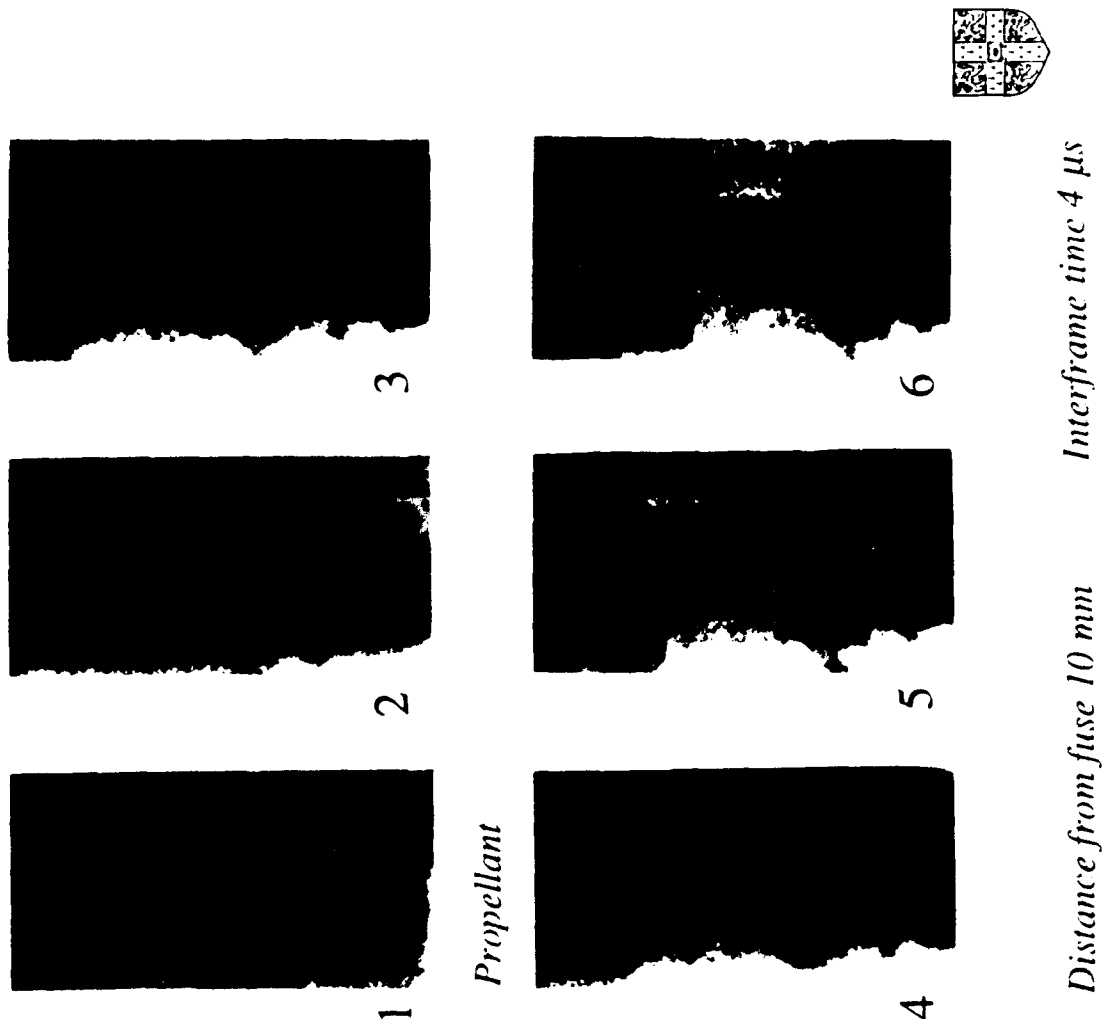
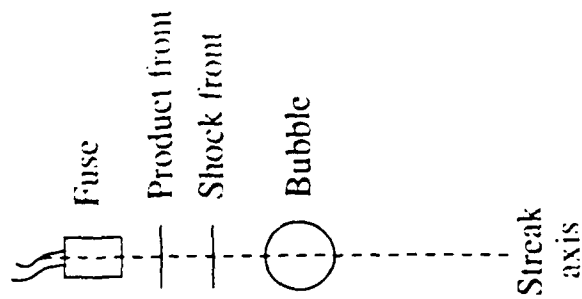
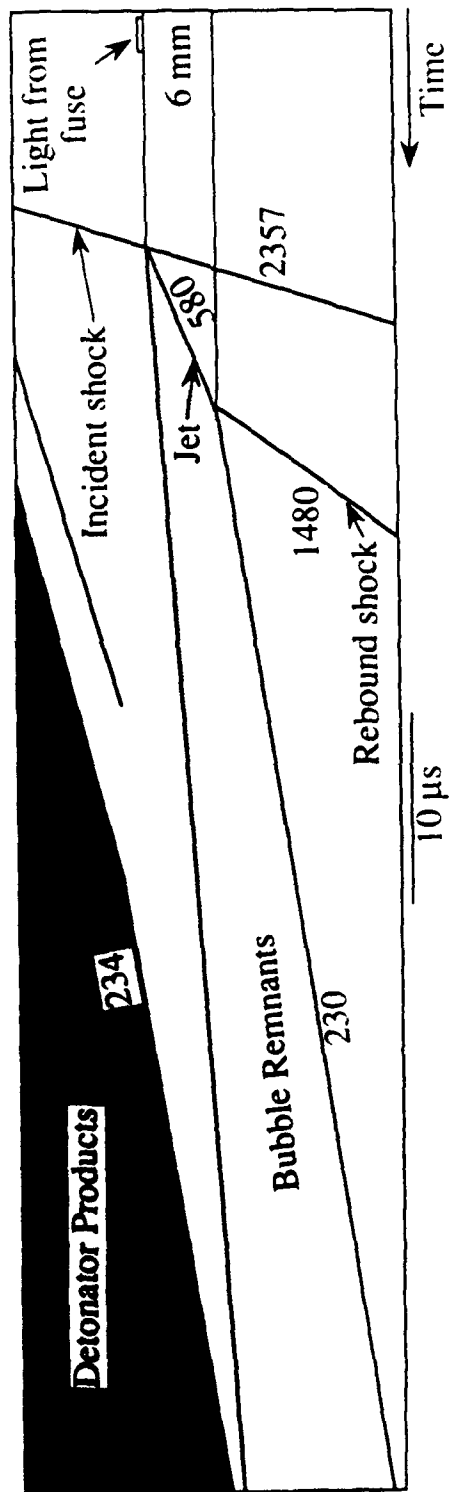
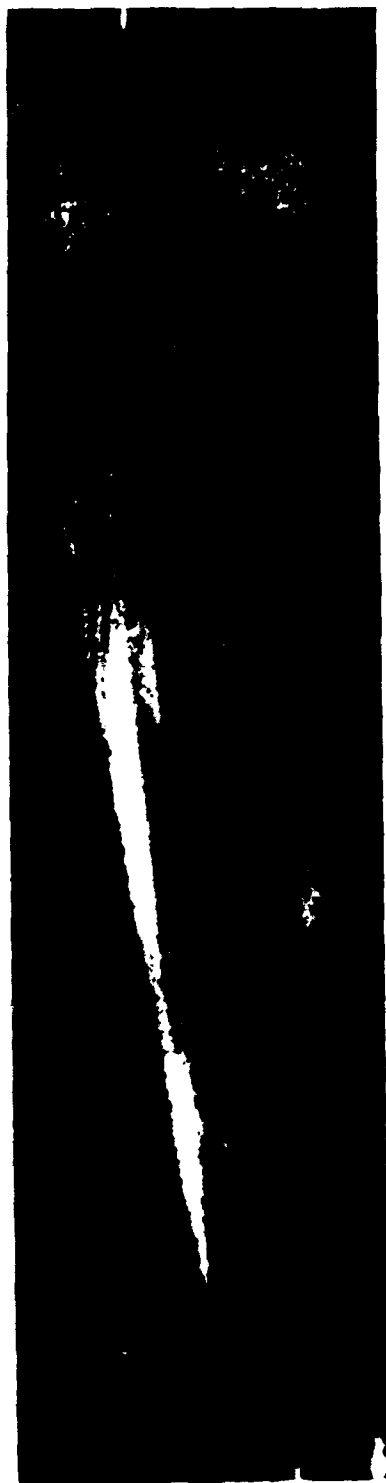


Figure 6. A cavity collapses 10...m from the fusehead. It is believed that initiation has occurred in the propellant (gas production evident at the downstream cavity wall). This was the only recorded incident of ignition.



Distance from fuse 10 mm

Figure 7. Streak picture showing the collapse of a 6 mm cavity in water. A schematic below has the velocities marked in m s^{-1} . The calibration scale for the time axis is shown.

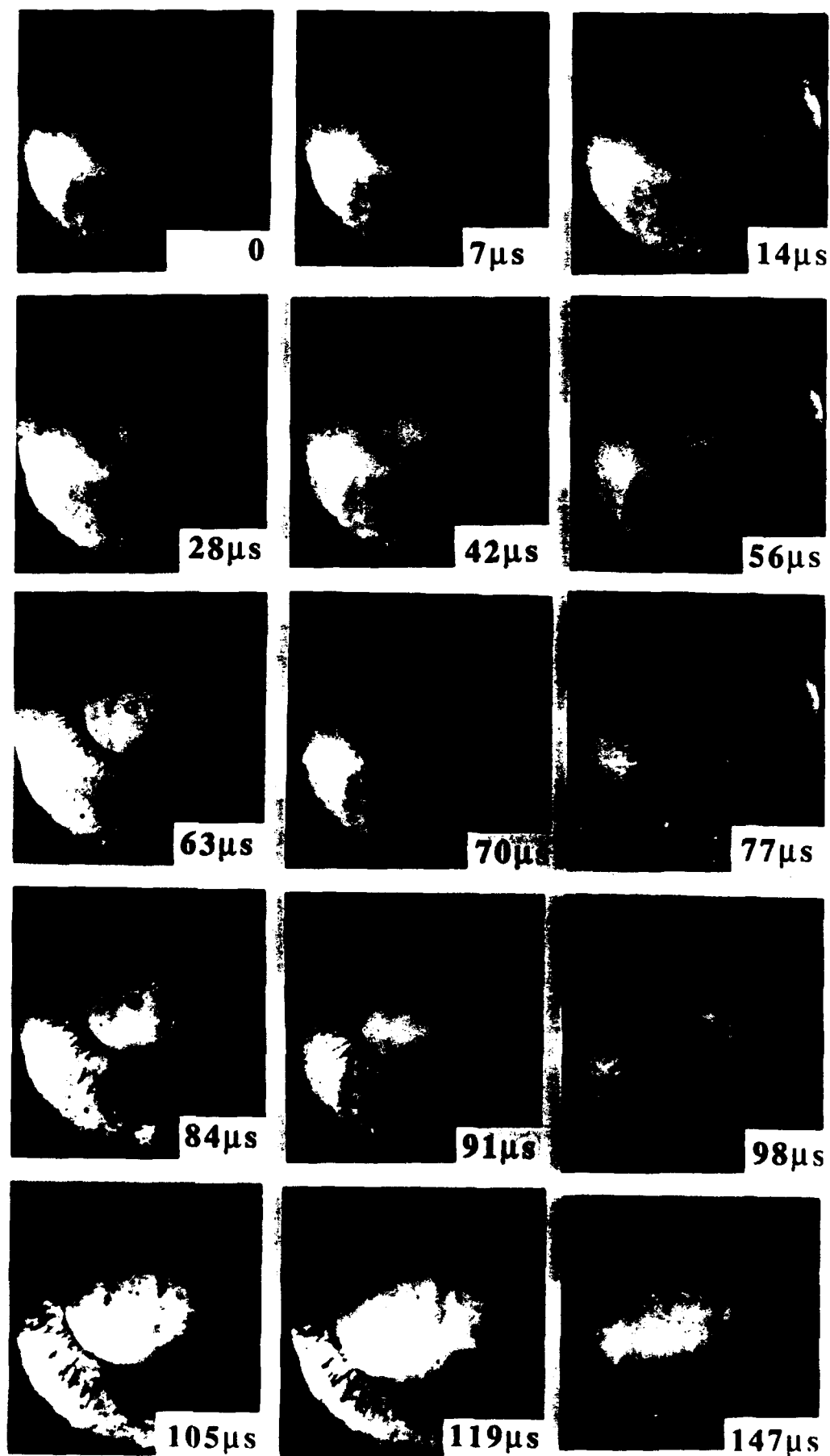


Figure 9. Selected frames from the high speed photographic record of the rapid deformation of a single drop of propellant.

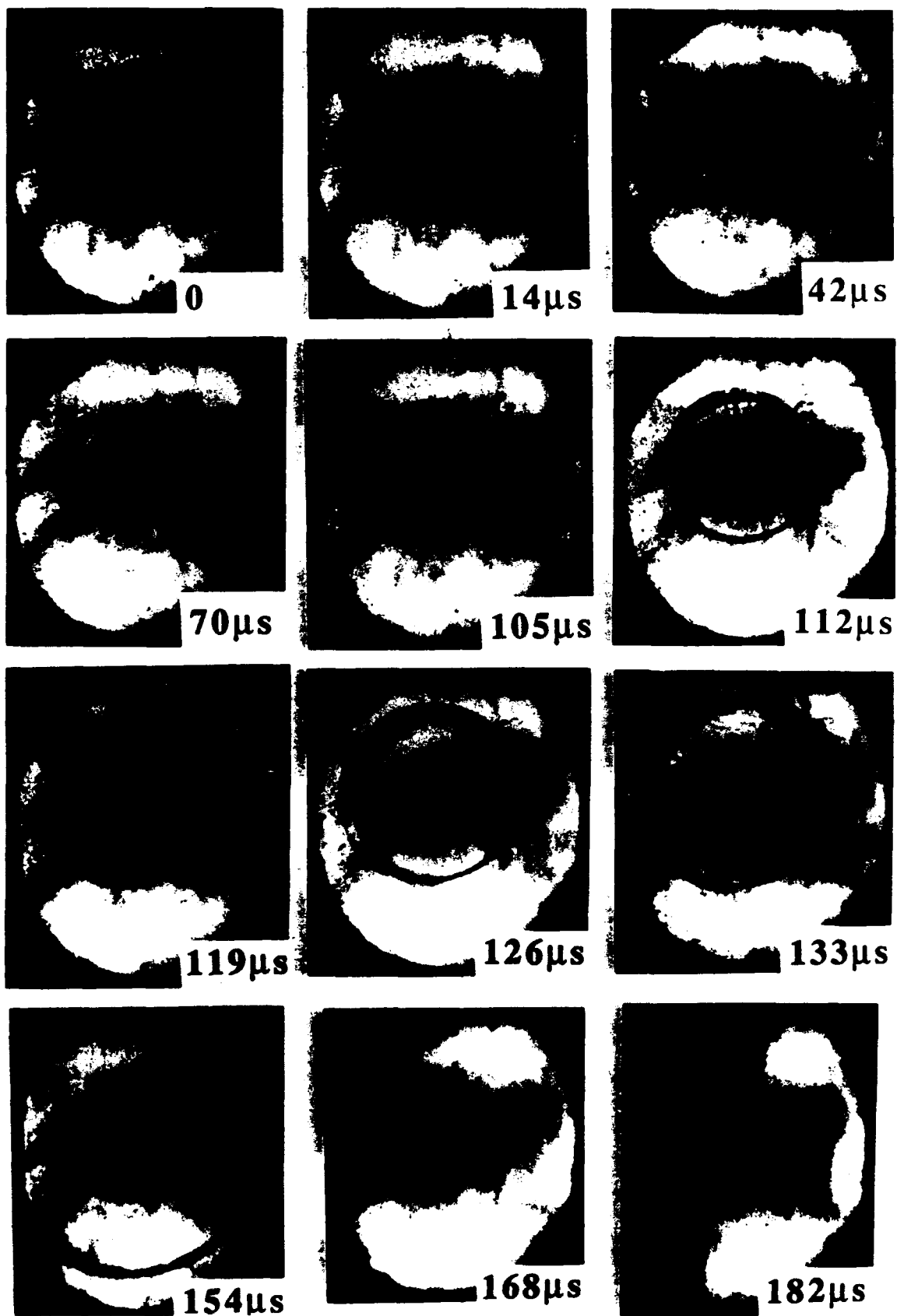


Figure 10. Selected frames from the high speed photographic record of the rapid deformation of a single drop of propellant.

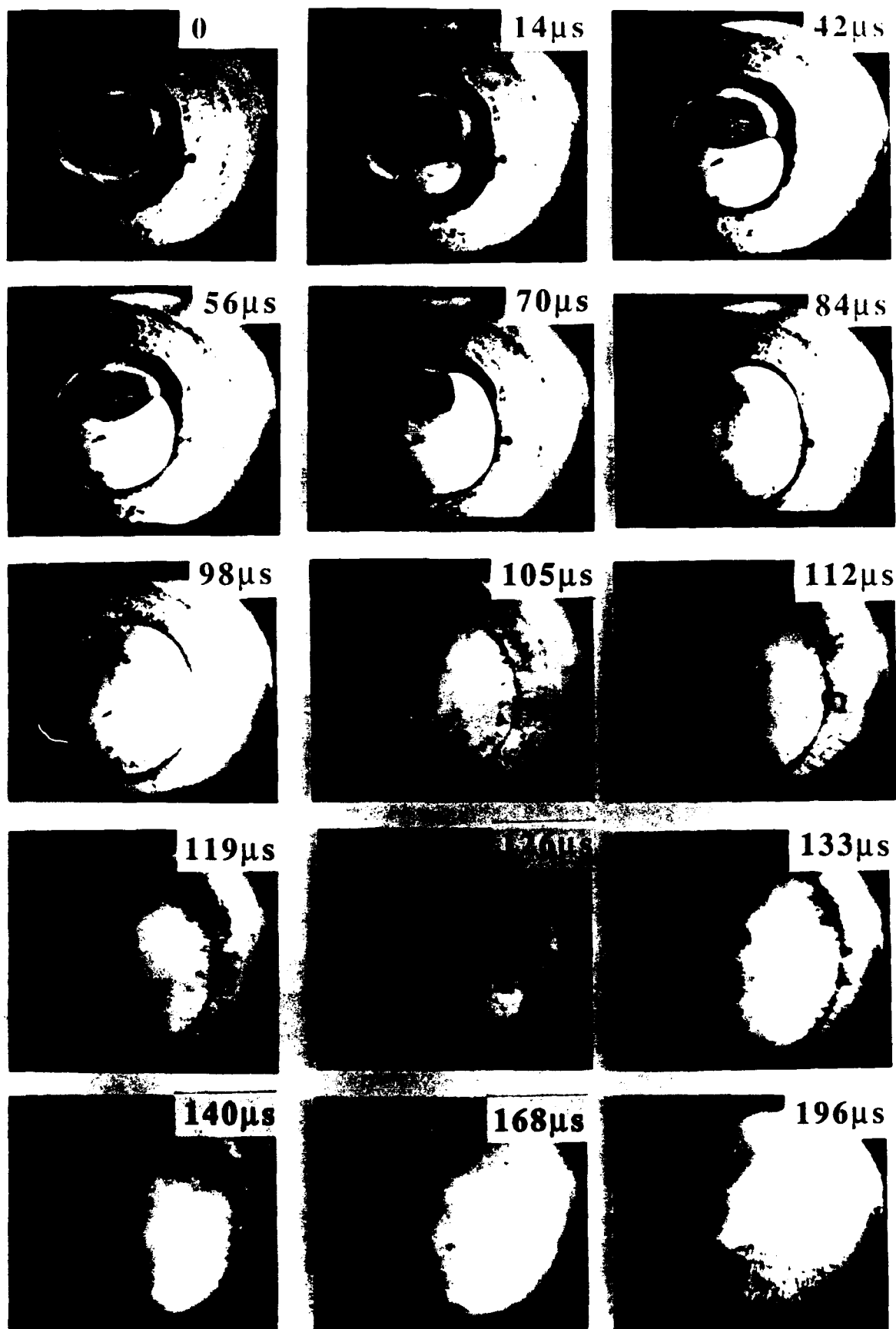


Figure 11. Selected frames from the high speed photographic record of the rapid deformation of an annulus of propellant stabilised by petroleum jelly. Note that because the liquid ring does not have a uniform thickness, the region of contact spreads round during the first few frames.

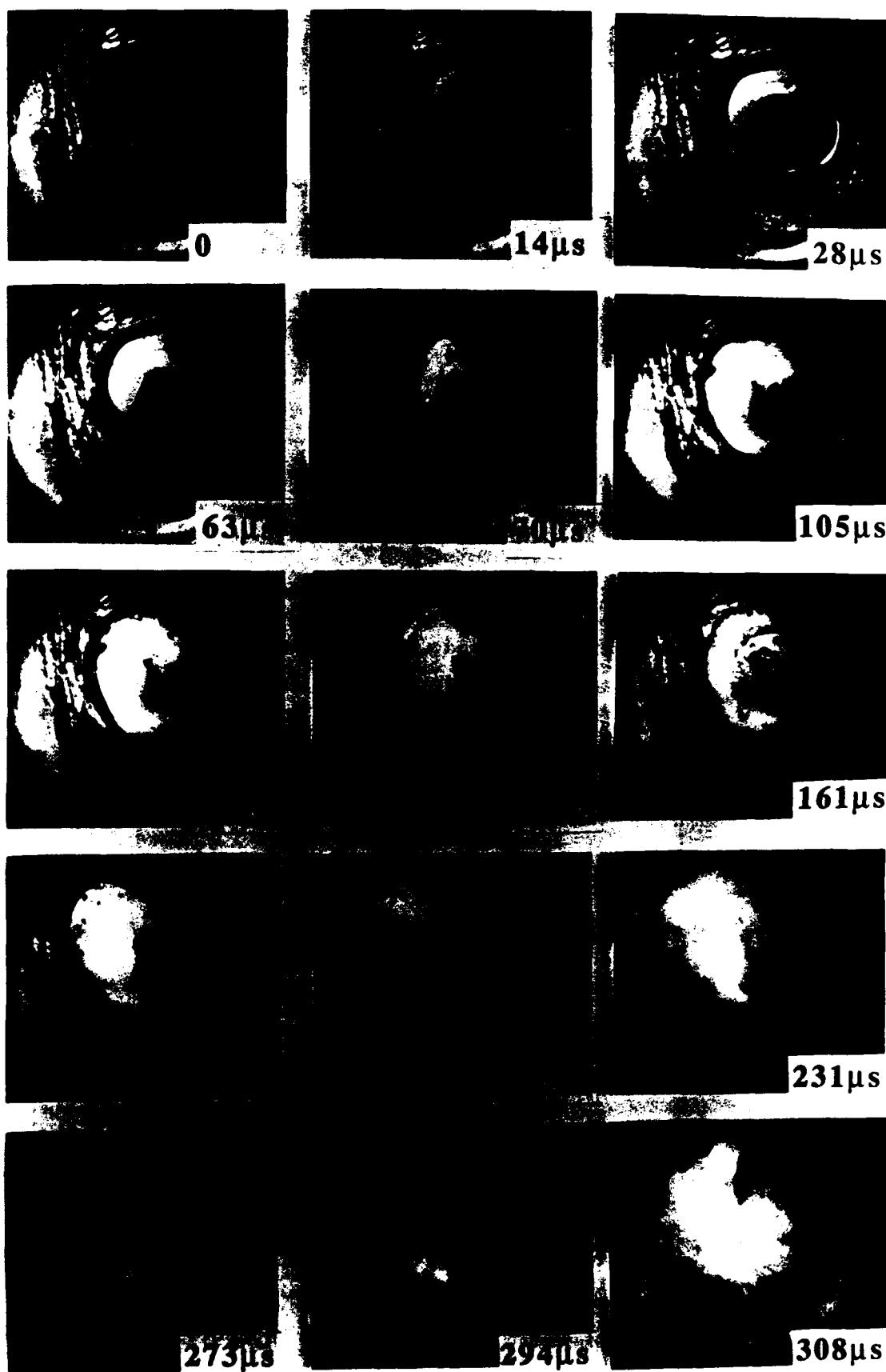


Figure 12. Selected frames from the high speed photographic record of the rapid deformation of an annulus of propellant stabilised by petroleum jelly. Note that because the liquid ring does not have a uniform thickness, the region of contact spreads round during the first few frames.

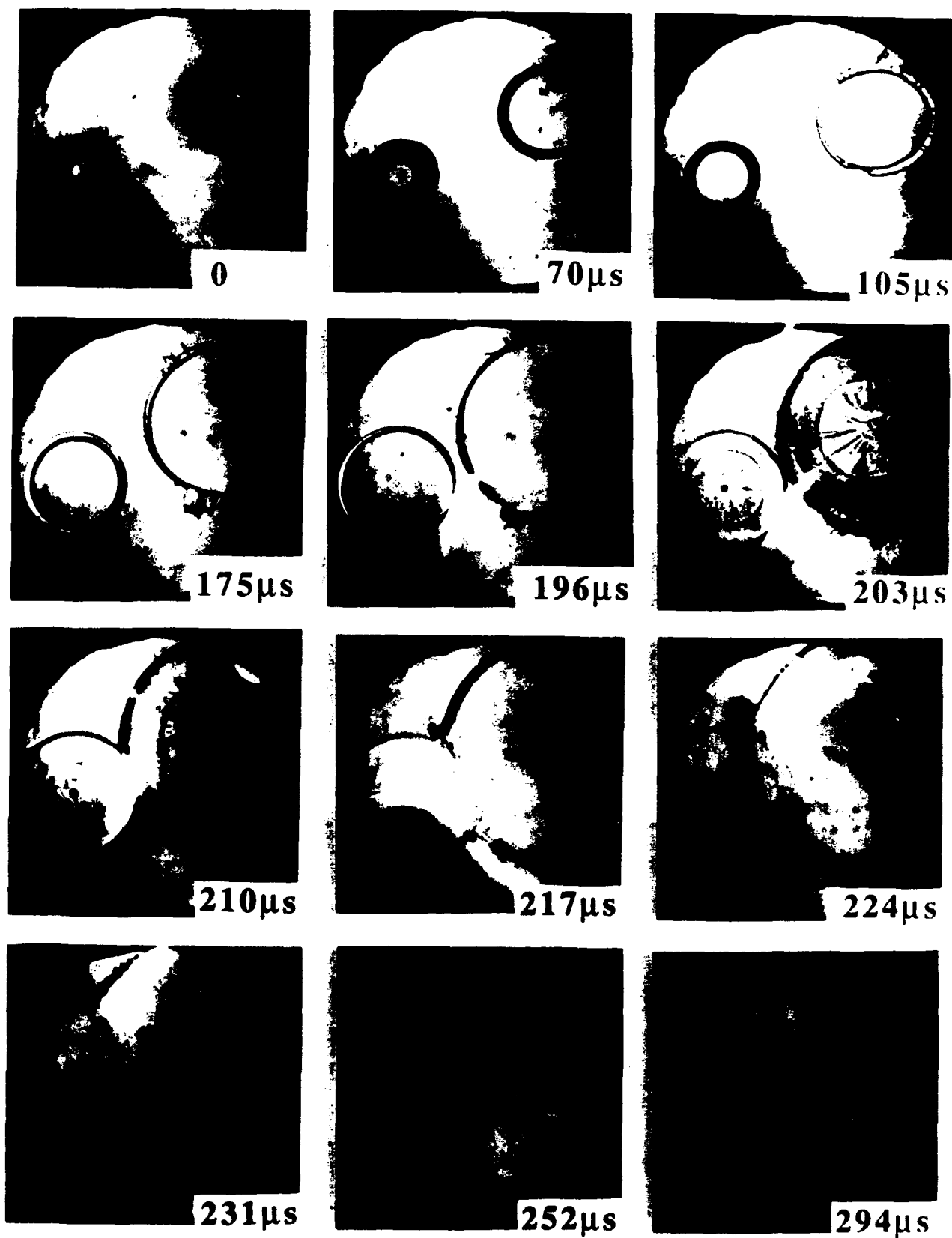


Figure 13. Selected frames from the high speed photographic record of the rapid deformation of two drops of propellant. Note the jetting that occurs when the drops make contact from 217 μs onwards.

Bubble collapse and the initiation of explosion†

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Experiments were conducted to investigate the initiation of an emulsion explosive containing cavities. Cylindrical cavities were created in thin sheets of either gelatine or an ammonium nitrate/sodium nitrate emulsion confined between transparent blocks. Shocks were launched into the sheets with either a flier-plate or an explosive plane-wave generator so as to collapse the cavities asymmetrically. The closure of the cavities and subsequent reaction in the explosive was photographed by using high-speed framing cameras. The collapse of the cavity proceeded in several stages. First, a high-speed jet was formed which crossed the cavity and hit the downstream wall sending out a shock wave into the surrounding material. Secondly, gas within the cavity was heated by rapid compression achieving temperatures sufficient to lead to gas luminescence. Finally, the jet penetrated the downstream wall to form a pair of vortices which travelled downstream with the flow. When such a cavity collapsed in an explosive, a reaction was observed to start in the vapour contained within the cavity and in the material around the heated gas. The ignition of material at the point at which the jet hit was found to be the principal ignition mechanism.

1. Introduction

The initiation of reaction in an explosive is a thermal process. Bowden & Yoffe (1952, 1958) and co-workers explained how mechanical energy dissipated by the passage of a shock wave through an explosive can be degraded into heat in order to cause ignition. They showed that bulk heating of a material may be insufficient to cause ignition but that heating in small, localized regions, called hot spots, would allow energy concentrations from which thermal explosion could proceed. They identified several mechanisms that lead to hot-spot formation including, frictional heating at the confinement boundaries, at the surface of adjacent explosive grains or at the surface of contaminant grit particles, viscous heating of the explosive at high flow-rates during impact and adiabatic compression of entrapped gas by shock waves.

Later studies have identified other mechanisms leading to hot-spot formation. Winter & Field (1975) impacted single crystals of silver and lead azide with small particles and concluded from critical conditions of particle size and impact velocity that initiation must have occurred in hot-spots produced by adiabatic shear. Similar results were obtained by Heavens & Field (1974). In a much wider study, Field *et al.* (1982) impacted various explosives in an adapted drop-weight machine and observed hot-spots caused by a wide variety of effects including adiabatic shear of the explosive, adiabatic compression of trapped gas, viscous flow, fracture of added particles and triboluminescent discharge. Further evidence for a shear-banding initiation mechanism in drop-weight tests is presented in Krishna Mohan *et al.*

† This paper was accepted as a rapid communication.

(1989). In studies on liquid explosives, Coley & Field (1973) were able to demonstrate the important roles of cavity collapse in both the initiation of fast reaction and the transition to low velocity detonation. Coffey (1985, 1989) has attributed energy localization in hot-spots during plastic deformation of a solid crystal to dislocation motion and pile-up. Chaudhri *et al.* (1982) and Chaudhri (1989) reported initiation of a fresh emulsion explosive caused by collapsing a glass bubble with a 2 GPa shock. They attributed the initiation to a hydrodynamic phenomenon: the impact of a high-speed microjet formed by the collapsing cavity, and suggested that the jet was heated by shock compression. Recent work has demonstrated hot-spots formed at absorbing centres after laser irradiation of secondary explosives (Ng *et al.* 1986; Östmark 1985; Renlund *et al.* 1989; Paisley 1989). With sufficiently heavy confinement, Tasaki *et al.* (1989) have realized a single-stage detonator containing a secondary explosive initiated by a laser pulse.

Cavity collapse has been studied for many years to explain the cavitation-erosion of hydraulic machinery and ship propellers. The earliest studies include the contributions of Besant (1859) and Rayleigh (1917) to a mathematical understanding of the symmetrical collapse of a single, isolated cavity. Kornfeld & Suvorov (1944) were the first to suggest that cavities might collapse asymmetrically to form a liquid jet while theoretical and experimental results in which a 'tongue of liquid' was found to be projected into bubbles accelerated in a gravitational field were presented by Walters & Davidson (1962, 1963). Benjamin & Ellis (1966) observed the formation of a liquid microjet in their classic photographic study and provided a theoretical discussion of the asymmetric collapse. The flow perturbations of an adjacent solid boundary were shown to give rise to a liquid jet directed towards the solid surface in calculations by Plesset & Chapman (1971). It is important to differentiate asymmetric collapses in which the jet results from a constant pressure gradient across the cavity from those in which the jet is a consequence of the transient pressure pulse from a shock wave. In the latter case, as in the present work, a jet is formed which travels in the direction of the shock front (Dear 1985; Dear & Field 1988; Bourne 1989; Bourne & Field 1989).

Pore space is found within an explosive charge both by accident and design. Pressed granular explosives contain cavities with sizes in the range of 10–100 μm . Cast explosives contain bubbles formed by stresses induced during recrystallization and by differential cooling rates at the confinement–explosive boundary. Polymer bonded explosives (PBXs) are largely cavity free when unloaded but debond at the crystal–binder interface when stressed to leave cavities (Field *et al.* 1985). Emulsion explosives are deliberately sensitized to ignition by the addition of small (*ca.* 10–100 μm diameter) glass spheres, whilst prilled ammonium nitrate is added to fuel oil trapping gas within the prill volume. In all cases, the collapse of pore volume may lead to the ignition of the material.

Gas compression within an explosive was identified as a cause of hot-spots in the work of Bowden & Yoffe (1952) and more recently in that of Chaudhri & Field (1974) and Starkenberg (1981). Bowden & Yoffe considered that the trapped gas was compressed sufficiently rapidly in a shock interaction that the process was adiabatic. Chaudhri & Field (1974) altered the gas content of bubbles attached to single crystals of silver and lead azide and pentaerythritol tetranitrate (PETN) and found that this variation of γ , the ratio of the specific heat capacities, could be used to enhance or inhibit initiation when the bubble was subsequently collapsed. They concluded that in their investigations adiabatic compression was the principal cause of ignition.

It may be noted that the value for γ taken in calculations of temperature should be modified since the number of degrees of freedom available to the molecules of a rapidly compressed gas is reduced. This increases the value of γ and thus elevates the temperatures achieved.

Starkenbergh (1981) differentiated between two régimes. In adiabatic compression, a high temperature reservoir was created by a very rapid collapse which subsequently heated an adjacent explosive layer to the point of ignition. Alternatively, if the collapse occurred more slowly over 0.1–1 ms (as was the case in Bowden & Yoffe's work) considerable energy was lost by conduction and convection during the process. Starkenbergh suggested that an adiabatic gas-heating model was insufficient to explain ignition in rapid collapses and hypothesized a more comprehensive analysis which included other parameters such as the pressurization rate of the gas at the solid surface and the dimensions of the gas space. He pointed out that heat conduction calculations could only be accurate if the increase of the heat conductivity of the gas with pressure was taken into account and that some gases (such as methane) were more efficient than others at transferring their heat across an explosive boundary even though they had a lower value of γ .

Seay & Seely (1961) reported that the shock initiation of a pressing of granular PETN was insensitive to varying the γ of the gas contained in the pore space of the explosive. They also lowered the pressure of the air in the interstitial sites, again without altering initiation thresholds. However, calculations for the ignition of lead azide presented by Chaudhri & Field (1974) suggested that if collapse times were sufficiently slow (*ca.* 100 μ s) then conduction was important. Johansson (1958) calculated the increase in temperature around a gas cavity due to heating from the compressed gas and showed it to be insufficient to cause ignition. He hypothesized that small drops were spalled into the hot gas from the collapsing cavity walls and that the increase in temperature due to reaction of these particles was sufficient to ignite the surrounding mass of explosive. It should be noted that any cavity will contain vapour from the surrounding medium and that when cavities are small, it is unlikely that the conduction of heat from the hot gas within the cavity into the explosive material is fast enough to allow ignition to occur. It seems probable, therefore, that examples in which ignition events have been so attributed have been due to other process.

Work due to Swallowe, presented by Dear *et al.* (1988), showed a crystal of a primary explosive placed in the downstream cavity wall (at the point at which the jet would strike) of a 3 mm, two-dimensional bubble initiated by the collapse of the cavity. When the experiment was repeated hitting an unconfined azide crystal with an equivalent liquid jet no initiation was observed. The authors attributed the initiation to the adiabatic compression of the gas in these large cavities.

Taylor (1985) studied the shock initiation of three grades of hexanitrostilbene (HNS). He described experimental evidence in which coarse-grained material (average pore size 5.30 μ m) was found to initiate less readily than a medium grade (average pore size 0.61 μ m). A further fine-grained material (average pore size 0.15 μ m) was found anomalously to be less sensitive than the medium grained material. These results and those presented in the rest of this section indicate the difficulties encountered in understanding the particular mechanisms responsible for ignition when cavities collapse within energetic materials.

Johnson (1986) attempted an analytical analysis of hot-spot initiation under various pressure régimes. He adopted an approach which avoided any discussion of

the formation of the hot spots by assuming their pre-existence at an elevated temperature within the bulk of the explosive and analysed their subsequent behaviour. The numerical analysis of growth of reaction to detonation in inhomogeneous explosives has been attempted by many, but most notably by Mader *et al.* (1967), Mader (1979), Mader & Kershner (1985, 1989). In his early work Mader considered the collapse of single, two-dimensional cavities in inert and reactive media. He showed that for small cavities at high shock pressures, gas effects were negligible and that hydrodynamic mechanisms gave rise to the high temperatures calculated around the point at which impact of the jet occurred. In recent years his two-dimensional analyses have been extended to three dimensions. His models show that it is the material in the region ahead of the downstream cavity wall that forms the hot-spot and that reaction in this area must be supported by that at adjacent sites if the initiation is to grow into a deflagration.

Frey (1985) presented a model whereby initiation of a solid explosive occurred by single cavity collapse. His work was based on Carroll & Holt's analysis (1972; Butcher *et al.* 1974; Carroll & Kim 1986) of the collapse of a cavity in an incompressible elastic-plastic medium in which there were several contributions to the temperature rise in the explosive. He assumed, in the most general case, that a gas-filled cavity was situated in a material with elastic-plastic behaviour and identified the following contributors to temperature rise: (i) gas phase heating; (ii) hydrodynamic effects resulting from the compressibility of the material; (iii) inviscid plastic work done in overcoming the yield strength of the material; (iv) visco-plastic work depending on the viscosity of the material.

The results of Frey's model showed various features of the collapse process. Hydrodynamic heating was significant when the strength or viscosity of the medium was insufficient to prevent the radial collapse from being violent enough to cause high-speed jetting or in the symmetric case, high radial velocities. Viscous heating dominated over that generated by inviscid-plastic work when cavities were less than 1 μm in diameter. In a similar model, Butler *et al.* (1989) added chemical decomposition.

Past work has demonstrated that the pore-size and the transport properties of the surrounding material greatly influence the principal mechanism by which the explosive ignites. In the present work the cavity size is large and the shock pressure is high while the emulsion is of relatively low viscosity. Hydrodynamic heating in the region struck by the jet and adiabatic heating in the compressed gas may be expected to be the principal ignition mechanisms.

2. Experimental

A method by which liquid drop impact phenomena can be studied two dimensionally was proposed by Brunton (1967). He suggested that discs might replace drops and with Camus designed an apparatus in which a disc of water was held under its own surface tension between two glass blocks and impacted with a metal slider (Brunton & Camus 1970; Camus 1971). The technique was adapted by Dear (1985) to use water with 12% by weight gelatine which gave more accurate control over the geometry of the drops. Dear later used the method to look at other liquid geometries such as wedges and a few simple cavity collapse configurations (Dear 1985; Dear & Field 1988).

The advantage of studying bubble collapse two dimensionally was that details of

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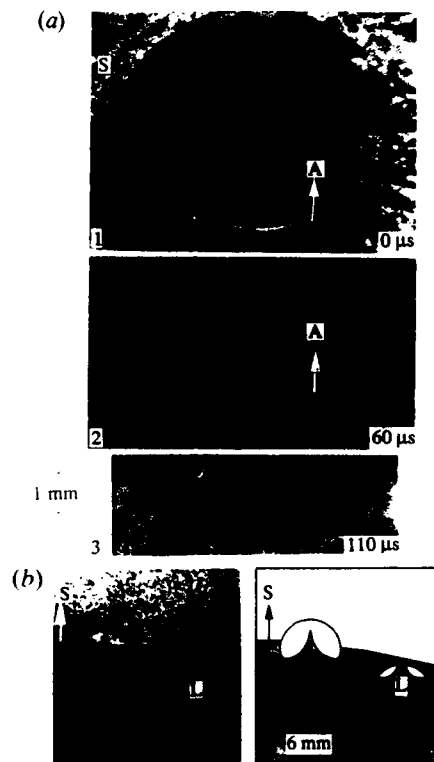


Figure 1. The asymmetrical collapse of cylindrical, air filled bubbles in gelatine. (a) The incident shock, S, of pressure 0.26 GPa, collapses a 12 mm cavity. Note the air shock, A, bouncing within the cavity and the formation of a jet which strikes the downstream wall in frame 3 isolating two lobes of entrapped gas. (b) The shock, of strength 1.88 GPa, collapses a 6 mm cavity. The jet is crossing the left-hand cavity faster than the incident shock is moving. A second cavity on the right has already collapsed and two points of light are seen from the trapped lobes of luminescing gas.

At higher shock pressures the basic features of collapse behaviour are preserved. However, three variations are worthy of note. Firstly, the jet no longer travels at constant velocity. Secondly, the jet velocity can exceed that of the collapsing shock. Thirdly, the gas can be sufficiently compressed that temperatures can rise sufficiently to allow gas-luminescence. A more detailed account of the collapse behaviour of single cavities at varying pressures is given in Bourne & Field (1991).

(b) High temperatures in collapsing cavities

Figure 2a shows three frames from a sequence in which a single 6 mm cavity collapses after interaction with a 1.88 GPa shock. The interframe time is $0.2 \mu\text{s}$ and the exposure time for each frame is 20 ns. The cavity is approaching the final stages of collapse and is hidden behind the collapse shock-front. In frame 1 a single flash of light, J, is seen. In frame 2 no luminescence is observed. In frame 3 two flashes, L, are seen. The dark cusp to the right of the frame is an artefact introduced by the display circuitry of the camera. The schematic shows the relative positions of the three points of luminescence. The first corresponds to the impact of the jet at the downstream wall, whilst the other two correspond to the position of the lobes of trapped gas isolated by jet penetration of the downstream wall as in figure 1b.

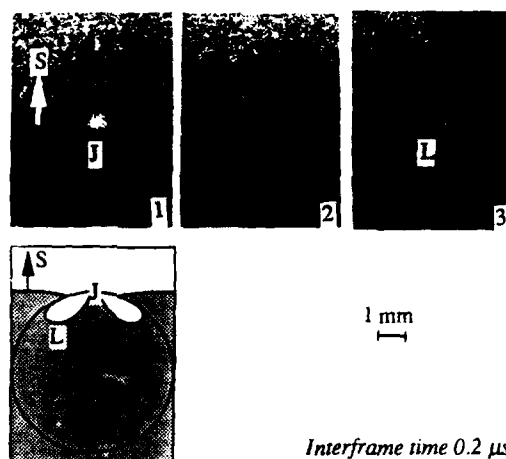


Figure 2. Three consecutive frames of the collapse of a 6 mm cavity in gelatine by a 1.88 GPa shock. S. Frame 1 shows the luminescence, J, from gas trapped between the jet tip and the downstream cavity wall just before the jet strikes the downstream wall. The luminescence is not apparent in frame 2. By frame 3 two lobes of entrapped gas, L, have been isolated and begin to luminesce. The schematic indicates the relative positions of the flashes J and L.

The first flash of light is believed to be due to the violent shock heating of a pocket of gas trapped between the jet and the downstream cavity wall at the moment before impact. The luminescence has been attributed by Walton (in Dear *et al.* 1988) to 'free radical creation and radiative recombination'. This places a lower limit of *ca.* 800 K on the temperature of the contained gas. Bowden & Yoffe (1952) suggested that 700 K was the minimum temperature needed within a collapsed bubble to initiate an explosive. Spectroscopic measurements of the temperatures reached within a hot-spot in an explosive have been made by several workers (e.g. Von Holle & Tarver 1981) yielding values of between 600 and 1600 K. It is clear that ignition temperatures can be reached during the final stages of cavity collapse in the present experiments.

(c) Hot-spot formation in an emulsion explosive

The sequence of figure 3 shows two frames from a high-speed sequence in which four cavities, two of diameter 5 mm and two of diameter 8 mm, are collapsed by a shock of pressure 8 GPa (leaving the PMMA attenuator). The sequence is unlit, the recorded illumination being due to reaction. The cavities are arranged at the corners of a square. On the first row is a 5 mm cavity at the top left of the frame and an 8 mm cavity below it. On the second row is an 8 mm cavity at the top right of the frame and a 5 mm cavity below it. The interframe time is 1 μ s and the exposure time for each frame is 0.1 μ s. Schematic diagrams of the same scale are placed to the right of each picture. The collapsing shock has entered from the left-hand side of the sequence and in the first frame, the shock has completely collapsed the small cavity at the top left of the frame. A flash of light, R, can be seen centred upon the point of jet impact. The downstream portion of the lower cavity is still visible but the centre portion contains a dark area, J, corresponding to the position of the jet. Reaction has not started ahead of this point suggesting either that the jet has not yet hit or that an induction period exists after the jet impacts before the reaction begins. Above the jet is an area of reaction, G, in the vapour within the cavity. Below the jet, a small amount of reaction, W, takes place in the emulsion adjacent to the cavity wall. In

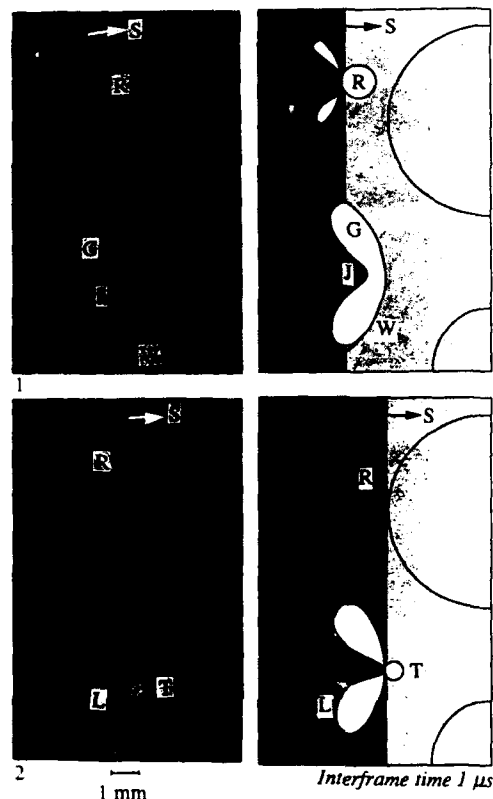


Figure 3. An array of four cavities of diameter 5 mm and 8 mm in an emulsion explosive is collapsed by a shock, S, running from left to right. In frame 1 the upper cavity has collapsed and a region of reaction, R, has been initiated. The lower cavity, in the final stages of collapse, shows reaction in area G, the vapour contained within the cavity, and W the material adjacent to the heated downstream wall. A schematic to the right of the frame shows the relative position of the cavities and reaction sites. In frame two, the upper cavity has finished reacting. Reaction begins at T, a region in the emulsion ahead of the point where the jet strikes. The sequence is unlit.

the second frame, the shock, S, has moved further across the frame and to the right. The reaction site, R, ahead of the upper bubble has extinguished. However, reaction in the lower bubble, T, proceeds at the point of jet impact. Areas adjacent to the trapped lobes of hot gas, L, do not begin to react. The ignition site is centred in the material directly ahead of the impacting jet, J, in frame 1.

The sequence shows several features of cavity collapse commented upon by other workers. There is evidence of reaction occurring in the explosive vapour trapped in the hot lobes of gas as suggested by Johansson (1958). Also heat conduction into the surrounding material has caused some reaction. However, the principal ignition mechanism in this situation appears to be the impact of the jet. Hydrodynamic compression of the material at the downstream wall causes the temperature rise necessary to trigger the onset of reaction. In these experiments reaction sites have a lifetime of *ca.* 5 μ s and reaction is occurring ahead of the collapse shock, S, at both sites, indicative of the supersonic jet velocities achieved.

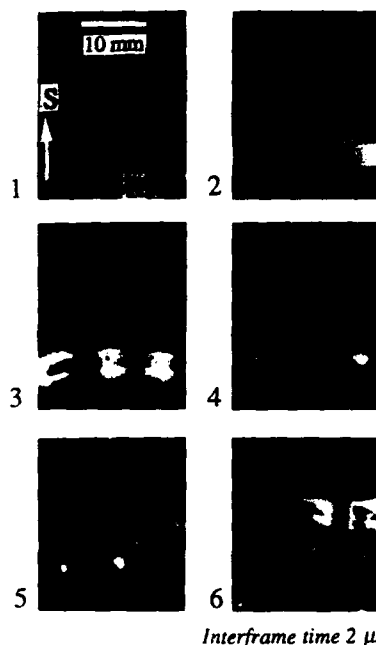


Figure 4. The collapse of a 3×3 square array of 5 mm cavities punched into the emulsion. The shock, S, enters from below causing two points of reaction, R, on the upstream wall. A double image occurs here and with other reaction sites because of refraction through the shock in the confining blocks. Collapse of the array proceeds row by row with reaction sites ahead of the incident shock. The average lifetime of sites is $5 \mu\text{s}$. The sequence is unlit.

(d) *The collapse of a cavity array in an emulsion explosive*

Figure 4 shows the collapse of a 3×3 square array of 5 mm cavities punched into the emulsion. The shock, S, enters from below and is of the same pressure as before. Again the emulsion is sandwiched between PMMA blocks and spacers confine the emulsion at the sides. The interframe time is $2 \mu\text{s}$ and the exposure time for each frame is $0.1 \mu\text{s}$. The shock, S, can be seen entering frame 1 below. The cavity on the right of the first row shows two points of light, R, at the shock front. These are believed to be two reacting sites produced at irregularities on the cavity wall. A double image of these sites is apparent, due to refraction through shocks running at different velocities in the PMMA confinement and in the emulsion. The material ahead of the point at which the jet strikes reacts in frame 2 and the sites, characteristically kidney-shaped, persist until frame 6. Again, double images occur. The second row is nearing the end of collapse in frame 5 and reaction is beginning in the central of the three cavities due to the slight curvature of the shock front. In the next frame the sites grow in the central and the right-hand cavities.

The collapse of cavity arrays was studied by Dear & Field (1988). They showed that a wave was formed which travelled through collapsing the array row by row. Bourne & Field (1990) calculated the velocity of such a wave and found it to be dependent upon the shock pressure, the cavity diameter and inter-cavity spacing. Only the first row of a square array is collapsed by the incident shock. The second row is collapsed by the shocks driven by the jets striking the downstream wall. Thus collapse proceeds in a row by row manner as observed in the sequence. As in §3c, the reaction sites are found in the material ahead of the downstream cavity wall. Also,

since the jet velocity can exceed the shock velocity, the reaction initiates ahead of the incident shock. The reacting region ignites at the point of jet impact but a propagating deflagration wave is not produced. The lifetime of the sites is at most 7 μ s and on average 5 μ s. The sequence presents a macroscopic picture of the heterogeneous reaction zone in a shocked explosive.

4. Conclusions

This study has presented a description of the collapse of cavities within inert and reactive media. Single cavities collapsed asymmetrically when shock waves passed over them forming a high-speed jet which travelled at constant velocity across the cavity and struck the downstream wall. This impact drove a second shock into the surrounding fluid which could run ahead of the collapsing shock when the latter was at sufficiently elevated pressure. Gas trapped within the cavity was heated rapidly during the closure achieving temperatures sufficient to cause luminescence when the compression rate was high. When the jet struck the downstream wall high transient temperatures were achieved in the liquid as it was hydrodynamically compressed, while as the jet penetrated the wall a pair of linear vortices formed which travelled downstream with the flow after the collapse was complete.

When such a cavity collapsed within an emulsion explosive several of the phenomena identified as leading to high temperatures competed to cause ignition of the material. Reaction was observed firstly within the vapour contained within the cavity in the final moments of collapse, secondly in the material adjacent to the heated gas at the downstream cavity wall and thirdly, and principally, by hydrodynamic heating of material at the point of impact of the high-speed jet. Such a mechanism is in accord with the model of Mader & Kershner (1989).

In cavity arrays, collapse proceeded in a wave triggered by the collapse of the outermost shell of cavities and propagated by subsequent collapse of inner shells by the rebound shocks from adjacent rows. Reaction sites were found to be ahead of the collapse shock, had an average lifetime of 5 μ s and died in the flow behind the shock. A wave (travelling close to the shock velocity) triggered reaction sites in the material ahead of the collapsing cavity layer. These sites persisted as reaction proceeded in the flow behind the collapse-front constituting a deflagration wave in the material. High void fractions gave many hot-spots but reduced the available material for reaction. Low void fractions gave scattered reacting sites which did not constitute a propagating deflagration.

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References

- Benjamin, T. B. & Ellis, A. T. 1966 The collapse of cavitation bubbles and the pressures thereby produced against solid boundaries. *Phil. Trans. R. Soc. Lond. A* **260**, 221-240.
- Besant, W. H. 1859 *Hydrostatics and hydrodynamics*. Cambridge University Press.
- Bourne, N. K. 1989 Shock interactions with cavities. Ph.D. thesis. University of Cambridge.
- Bourne, N. K. & Field, J. E. 1989 Cavity collapse in a heterogeneous commercial explosive. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 869-878.
- Bourne, N. K. & Field, J. E. 1990 Collapsing cavities in reactive and non-reactive media. In *Proc. of the 19th Int. Conf. on High-speed Photography and Photonics, Cambridge, September*. SPIE 1358. Washington. pp. 1046-1056.

- Bourne, N. K. & Field, J. E. 1991 Shock induced collapse of single cavities in liquids. *J. Fluid Mech.* (Submitted.)
- Bowden, F. P. & Yoffe, A. D. 1952 *Initiation and growth of explosion in liquids and solids*. Reprinted CUP, 1985.
- Bowden, F. P. & Yoffe, A. D. 1958 *Fast reaction in solids*. London: Butterworths.
- Brunton, J. H. 1967 Erosion by liquid shock. In *Int. Conf. Rain Erosion* (ed. A. A. Fyall & R. B. King), pp. 821-823. RAE, U.K.
- Brunton, J. H. & Camus, J.-J. 1970 The application of high-speed photography to analysis of flow in cavitation and drop-impact studies. In *Proc. Int. Conf. High-speed Photography* (ed. W. G. Hyzer & W. G. Chase), pp. 444-449. New York: SMPTE.
- Butcher, B. M., Carroll, M. M. & Holt, A. C. 1974 Shock-wave compaction of porous aluminium. *J. appl. Phys.* **45**, 3864-3875.
- Butler, P. B., Kang, J. & Baer, M. R. 1989 Hot-spot formation in a collapsing void of condensed-phase, energetic material. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 906-917.
- Camus, J.-J. 1971 High-speed flow in impact and its effect on solid surfaces. Ph.D. thesis. University of Cambridge.
- Carroll, M. M. & Holt, A. C. 1972 Static and dynamic pore collapse relations for ductile porous materials. *J. appl. Phys.* **43**, 1626-1636.
- Carroll, M. M. & Kim, K. T. 1986 The effect of temperature on visco-plastic pore collapse. *J. appl. Phys.* **59**, 1962-1967.
- Chaudhri, M. M. 1989 The initiation of fast decomposition in solid explosives by fracture, plastic flow, friction and collapsing voids. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 857-868.
- Chaudhri, M. M. & Field, J. E. 1974 The role of rapidly compressed gas pockets in the initiation of condensed explosives. *Proc. R. Soc. Lond. A* **340**, 113-128.
- Chaudhri, M. M., Almgren, L.-A. & Persson, A. 1982 High-speed photography of the interaction of shocks with voids in condensed media, SPIE vol. 348. In *15th Int. Cong. on High-speed Photography and Photonics, San Diego*, pp. 388-394.
- Coffey, C. S. 1985 Hot-spot production by moving dislocations in a rapidly deforming crystalline explosive. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, New Mexico*, pp. 62-67.
- Coffey, C. S. 1989 Initiation of explosive crystals by shock or impact. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 58-65.
- Coley, G. D. & Field, J. E. 1973 The role of cavities in the initiation and growth of explosion in liquids. *Proc. R. Soc. Lond. A* **335**, 67-86.
- Dear, J. P. 1985 The fluid mechanics of high-speed impact. Ph.D. thesis. University of Cambridge.
- Dear, J. P. & Field, J. E. 1988 A study of the collapse of arrays of cavities. *J. Fluid Mech.* **190**, 409-425.
- Dear, J. P., Field, J. E. & Walton, A. J. 1988 Gas compression and jet formation in cavities collapsed by a shock wave. *Nature, Lond.* **332**, 505-508.
- Field, J. E., Swallowe, G. M. & Heavens, S. N. 1982 Ignition mechanisms of explosives during mechanical deformation. *Proc. R. Soc. Lond. A* **383**, 231-244.
- Field, J. E., Palmer, S. J. P., Pope, P. H., Sundararajan, R. & Swallowe, G. M. 1985 Mechanical properties of PBXs and their deformation during drop weight impact. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, July*, pp. 635-644.
- Frey, R. B. 1985 Cavity collapse in energetic materials. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, July*, pp. 68-80.
- Heavens, S. N. & Field, J. E. 1974 The ignition of a thin layer of explosive by impact. *Proc. R. Soc. Lond. A* **338**, 77-93.
- Hutchings, I. M., Rochester, M. C. & Camus, J.-J. 1977 A rectangular bore gas gun. *J. Phys. E* **10**, 455-457.
- Johansson, C. H. 1958 The initiation of liquid explosives by shock and the importance of liquid break up. *Proc. R. Soc. Lond. A* **246**, 160-167.
- Proc. R. Soc. Lond. A* (1991)

- Johnson, J. N. 1987 Hot-spot reaction under transient pressure conditions. *Proc. R. Soc. Lond. A* **413**, 329–350.
- Kornfeld, M. & Suvorov, L. 1944 On the destructive action of cavitation. *J. appl. Phys.* **15**, 495–506.
- Krishna Mohan, V., Jyothi Bhasu, V. C. & Field, J. E. 1989 Role of adiabatic shear bands in initiation of explosives by drop-weight impact. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 1276–1283.
- Leiper, G. A. & Steele, A. F. 1984 Design and calibration of a PMMA gap test. ICI Rep. NR321A.
- Mader, C. L. 1979 Numerical modelling of detonations. University of California, Berkeley.
- Mader, C. L. & Kershner, J. D. 1985 The three-dimensional hydrodynamic hot-spot model. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, July*, pp. 42–52.
- Mader, C. L. & Kershner, J. D. 1989 The heterogeneous explosive reaction zone. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 693–700.
- Mader, C. L., Taylor, R. W., Venable, D. & Travis, J. R. 1967 Theoretical and experimental two-dimensional interactions of shocks with density discontinuities. Los Alamos National Laboratory Rep. LA-3614, February.
- Marsh, S. P. 1980 *LASL shock Hugoniot data*. University of California Press.
- Mitchell, A. C. & Nellis, W. J. 1982 Equation of state and electrical conductivity of water and ammonia shocked to the 100 GPa (1 Mbar) pressure range. *J. chem. Phys.* **76**, 6273–6281.
- Ng, W. L., Field, J. E. & Hauser, H. M. 1986 Thermal fracture and laser-induced decomposition of PETN. *J. appl. Phys.* **59**, 3945–3952.
- Östmark, H. 1985 The laser as a tool for sensitivity testing of explosives. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, New Mexico*, pp. 473–484.
- Paisley, D. L. 1989 Prompt detonation of secondary explosives by laser. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 1110–1117.
- Plesset, M. S. & Chapman, R. B. 1971 Collapse of an initially spherical vapour cavity in the neighbourhood of a solid boundary. *J. Fluid Mech.* **47**, 283–290.
- Rayleigh, Lord 1917 On the pressure developed during the collapse of a spherical cavity. *Phil. Mag.* **34**, 94–98.
- Renlund, A. M., Stanton, P. L. & Trott, W. M. 1989 Laser initiation of secondary explosives. In *Proc. Ninth Symposium (International) on Detonation, Portland, Oregon*, pp. 1118–1127.
- Seay, G. E. & Seely, L. B. 1961 Initiation of a low-density PETN pressing by a plane shock wave. *J. Appl. Phys.* **32**, 1092–1097.
- Starkenbergh, J. 1981 Ignition of solid high explosive by the rapid compression of an adjacent gas layer. In *Proc. Seventh Symposium (International) on Detonation*, pp. 3–16.
- Tasaki, Y., Kurokawa, K., Hattori, K., Sato, T., Miyajima, T. & Takano, M. 1989 Experimental study of laser-initiated detonator. In *4^e Congrès International de Pyrotechnie du Groupe de Travail de Pyrotechnie, La Grande Motte, 5–9 June*, pp. 225–230.
- Taylor, P. A. 1985 The effects of material microstructure on the shock-sensitivity of porous granular explosives. In *Proc. Eighth Symposium (International) on Detonation, Albuquerque, New Mexico*, pp. 26–33.
- Von Holle, W. G. & Tarver, C. M. 1981 Temperature measurement of shocked explosives by time-resolved infra-red radiometry - a new technique to measure shock induced reaction. In *Proc. Seventh Symposium (International) on Detonation*, pp. 993–1003.
- Walsh, J. M. & Rice, M. H. 1957 Dynamic compression of liquids from measurements of strong shock waves. *J. chem. Phys.* **26**, 815–830.
- Walters, J. K. & Davidson, J. F. 1962 The initial motion of a gas bubble formed in an inviscid liquid. Part 1. The two-dimensional bubble. *J. Fluid Mech.* **12**, 408–416.
- Walters, J. K. & Davidson, J. F. 1963 The initial motion of a gas bubble formed in an inviscid liquid. Part 2. The three-dimensional bubble and the toroidal bubble. *J. Fluid Mech.* **17**, 321–336.
- Winter, R. E. & Field, J. E. 1975 The role of localised plastic flow in the impact initiation of explosives. *Proc. R. Soc. Lond. A* **343**, 399–413.

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